THE EFFECTS OF INLET VELOCITY AND BARREL DIAMETER ON CYCLONE PERFORMANCE

A Thesis

by

WILLIAM BROCK FAULKNER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2006

Major Subject: Biological and Agricultural Engineering

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Approved by:

Chair of Committee, Bryan W. Shaw
Committee Members, Calvin B. Parnell, Jr.
Stephen Fuller
Head of Department, Gerald Riskowski

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ABSTRACT

The Effects of Inlet Velocity and Barrel Diameter on Cyclone Performance. (May 2006)

William Brock Faulkner, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Bryan W. Shaw

Cyclone separators are widely used in agricultural processing industries as air pollution abatement devices. The performance of cyclones is a function of the geometry of the cyclone, operating parameters, and the particle size distribution (PSD) of the entrained aerosol. Multiple models have been proposed to predict the performance of cyclones given different geometric proportions, but many of these models do not quantify changes in performance with changes in inlet velocity or cyclone diameter given fixed geometric proportions.

The Texas A&M Cyclone Design (TCD) method is a simple method for designing cyclones based on an inlet design velocity. The TCD method specifies "ideal" inlet velocities of 975 ± 120 m/min (3200 ± 400 fpm) and 914 ± 120 m/min (3000 ± 400 fpm) for 1D3D and 2D2D cyclones, respectively. However, there is evidence that higher dust collection efficiencies may be obtained from cyclones using different inlet velocities than those specified as the "ideal" velocity. Furthermore, the TCD method assumes that cyclone performance is independent of cyclone diameter.

The present research demonstrates that, for large particles, the collection efficiency of 15.24 cm (six inch) diameter 1D3D and 2D2D cyclones is similar for inlet velocities from 10.16 standard m/s (2000 fpm) up to the design velocity, with

significantly lower pressure drop at lower inlet velocities, resulting in lower energy requirements. However, the performance of cyclones is a function of cyclone diameter. Using similar operating parameters, the collection efficiency of a 60.96 cm (24 inch) diameter 1D3D cyclone was significantly lower ($\alpha = 0.05$) than that of a 15.24 and a 30.48 cm (6 and 12 inch) diameter cyclone, and the collection efficiency of a 91.44 cm (36 inch) cyclone was significantly lower ($\alpha = 0.05$) than that of a 60.96 cm (24 inch) diameter cyclone. The results of this research suggests the need for a new mathematical model to predict the performance of cyclones.

ACKNOWLEDGMENTS

There are innumerable people who have made it possible for me to be where I am today. Some of them worked hard to provide me with this opportunity, and many more have labored to instill good character and a good work ethic in me for which I am incredibly grateful. While there is not enough space here to acknowledge all of them by name, I appreciate the patience and persistence they had as well as the potential they seem to have found in me.

By the grace of God, He has allowed me to come to know and love His Son Jesus through whom I can approach Him with confidence. Having called me His child, He has put great people in my life to make me into the man He desires for me to be. I would like to thank several of those people by name:

To my wife, Brittney, I want to say thank you for encouraging me and being excited with me as I have worked to complete this degree. Thank you (and your parents) for trusting me to provide for you even as a graduate student. Your quiet confidence in me has been a steady impetus to work at all things well. Marriage to you has been more fun than I could have imagined, and I look forward to tackling the challenges of the future with you by my side!

To my Mom, I want to say thank you for loving me and continuing to believe in me. Thank you for having the foresight to plan for C.W. and me to be able to go to college and for disciplining us to live and learn on our own. I know that raising two boys after Daddy died was hard, but (while I'm biased) I think you did a great job! Your strength amazes me.

To my grandparents, I want to say thank you for teaching me to work hard and teaching me how important character and family are. If it wasn't for you, I would not have come to love working in agriculture as much as I do. And, I remember well all of the Little League games and elementary school plays that you came to; all of the weekends and summers I spent at the ranch; the 4-H projects and the family dinners. You have truly left an eternal legacy for all of your grandchildren.

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CHAPTER I

INTRODUCTION

Since the 1955 Air Pollution Control Act, the federal government has been concerned about air pollution in the United States. The establishment of the Environmental Protection Agency (EPA) and the passage of the Clean Air Act Amendments (CAAA) of 1970 marked major steps towards controlling air pollution. The CAAA required the EPA to establish National Ambient Air Quality Standards (NAAQSs), based on scientific studies, to protect the health (primary standards) and welfare (secondary standards) of the public. In the NAAQSs, the EPA in 1971 established the maximum levels of selected pollutants, known as criteria pollutants, that would lead to unacceptable air quality if exceeded (Federal Register, 1971). Another important part of the CAAA of 1970 was the mandate that the EPA write tough, national standards for new industrial plants to prevent weakened air pollution standards in one state from attracting new industry from another state. These New Source Performance Standards specify maximum emission rates for specific industries and are enforced by each state (Cooper and Alley, 2002).

Under Clean Air Act, State Air Pollution Regulatory Agencies (SAPRAs) are responsible for enforcing strict air pollution emission limits from certain sources, including agricultural processing facilities such as cotton gins and terminal export elevators. The limits enforced by the state must be at least as strict as the emission limits set by the Environmental Protection Agency (EPA) in the Code of Federal Regulations

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This thesis follows the style and format of the *Transactions of the ASAE*.

(Cooper and Alley, 2002). In order to uphold air pollution regulations, SAPRAs issue permits to emitting facilities. As long as a facility does not exceed Title V thresholds for pollutants, it is up to the state to decide what facilities are required to obtain permits.

The amount of a given pollutant that a facility is permitted to emit in a given year is determined based on published emission factors and an estimate of the performance of abatement devices employed. For example, the 1996 AP-42 factor for cotton gins is 1.39 kg total suspended particulate (TSP)/bale (3.05 #/bale). However, this emission factor assumes the use of covered condenser drums for all lint cleaning process streams and assumes a collection efficiency of 50 percent. If cyclones, which are assumed to have collection efficiencies of 90 percent by many states, are used in place of covered condenser drums, the emission factor per bale for that gin should be reduced accordingly. The factor by which the emission rate should be reduced can only be determined by scientific determination of the collection efficiency of an abatement device. Conversely, when a regulatory agency is determining whether a facility is in compliance with its permit without doing source sampling, it is important that the collection efficiency of the abatement devices in use be understood.

Cyclones are the most widely used air pollution abatement devices for removing particulate matter from air streams in agricultural processing industries and are slassified as Best Available Control Technology (BACT) for PM emissions from cotton gins in many states. The most commonly used cyclones are the 1D3D (Parnell and Davis, 1979) and 2D2D (Shepherd and Lapple, 1939) cyclones. The objectives of this research are to:

1. Characterize the collection efficiency and pressure drop associated with 1D3D and 2D2D cyclones across a range of inlet velocities, and
2. Determine the relationship between cyclone diameter and collection efficiency of 1D3D cyclones.

This research is intended to broaden the understanding of cyclone performance in order that agricultural industries may be regulated equitably and producers and managers may be able to select and operate particulate matter abatement systems that will best meet regulatory guidelines in an economically feasible manner.

This thesis is presented for consideration as a compilation of two manuscripts prepared to address the issues outlined above. The first objective of this work is specifically addressed by the manuscript in Chapter II, and the second objective is addressed by the manuscript in Chapter III. Appendix A discusses the publication status of both manuscripts used in this thesis.

CHAPTER II

EFFICIENCY AND PRESSURE DROP OF CYCLONES ACROSS A RANGE OF INLET VELOCITIES*

OVERVIEW

Cyclone separators are widely used in agricultural processing industries as air pollution abatement devices. The Texas A&M Cyclone Design (TCD) method is a simple method for designing cyclones based on an inlet design velocity. The TCD method specifies "ideal" inlet velocities of 975 ± 120 m/min (3200 ± 400 fpm) and 914 ± 120 m/min (3000 ± 400 fpm) for 1D3D and 2D2D cyclones, respectively. There is evidence that higher dust collection efficiencies may be obtained from cyclones using different inlet velocities than those specified as the "ideal" velocity. This paper quantifies the inlet velocities at which maximum collection efficiencies are obtained for 1D3D and 2D2D cyclones and the marginal pressure drop associated with reaching these collection efficiencies. It is demonstrated that for large particles, the collection efficiency of 15.24 cm (six inch) diameter 1D3D and 2D2D cyclones is similar for inlet velocities from 10.16 standard m/s (2000fpm) up to the design velocity, with significantly lower pressure drop at lower inlet velocities.

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INTRODUCTION

Cyclones are the most widely used air pollution abatement devices for removing particulate matter from air streams in agricultural processing industries. Relative to other abatement systems, cyclones have low initial costs, maintenance requirements, and energy consumption. Cyclones use centrifugal force to separate particulates from an air stream. A dust-laden air stream enters a cyclone tangentially near the top of the cyclone and flows downward in a spiral. Inertial and centrifugal forces act on the particulates, forcing them to the wall of the cyclone where they slide down the wall to the bottom of the cone and are removed. The air stream spirals to the bottom of the device, where it reverses direction and flows upward and out the top of the cyclone (Cooper and Alley, 2002).

The Lapple cyclone design method, often referred to as the standard cyclone design method, specifies the dimensions of a cyclone based on the barrel diameter. The most commonly used cyclones are the 2D2D (Shepherd and Lapple, 1939) and 1D3D cyclones (Parnell and Davis, 1979). The Ds in the 1D3D and 2D2D designations refer to the diameter of the cyclone barrel, while the numbers preceding the Ds refer to the length of the barrel and cone sections, respectively. A 1D3D cyclone, for instance, has a barrel length equal to the barrel diameter and a cone length equal to three times the barrel diameter. The design parameters for 1D3D and 2D2D cyclones are shown in Figure 1.

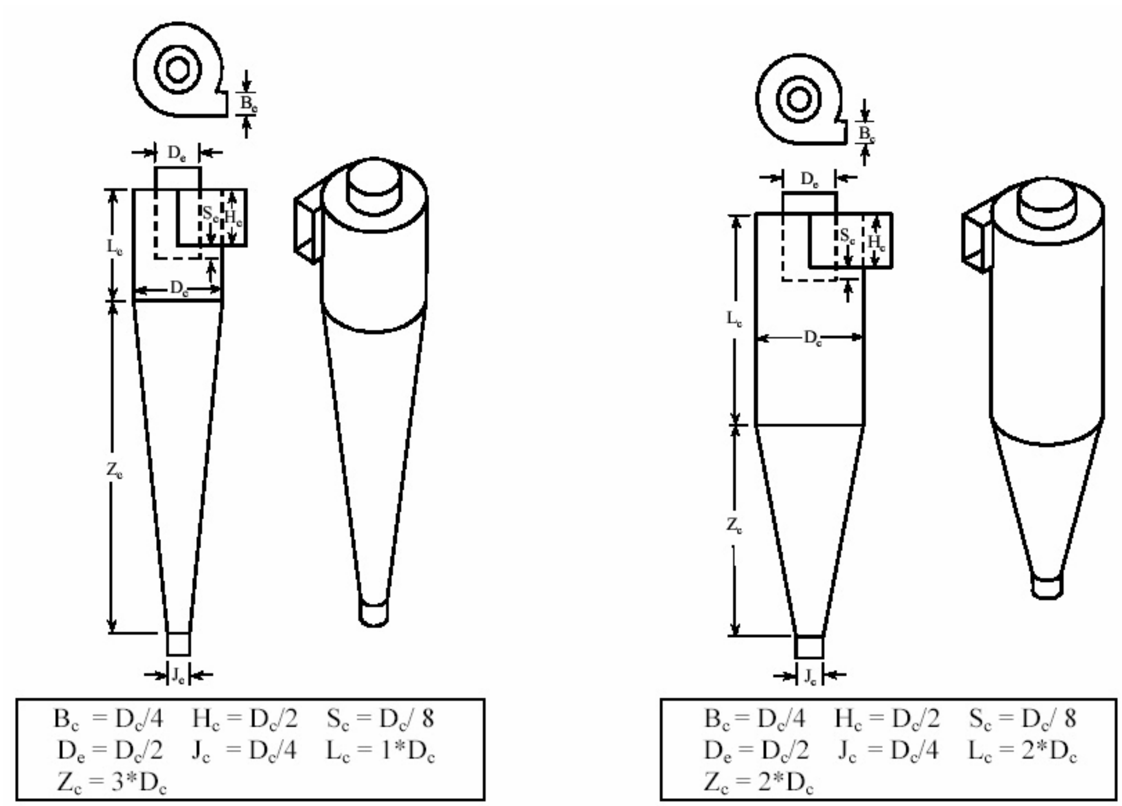


Figure 1. 1D3D and 2D2D cyclone layouts (Wang et al, 2003).

The Lapple cyclone design method also predicts the efficiency with which particles of a given size will be separated from the air stream. According to the Lapple method, dust collection efficiency increases unconditionally with increased air stream velocity. However, according to Parnell (1996), above a threshold airspeed, the vortex inside a cyclone becomes disturbed and collection efficiencies decline. Furthermore, Parnell (1996) indicates that the Lapple method significantly underestimates collection efficiency.

The efficiency of cyclone systems is a function of the particle size distribution (PSD) of entrained dust and the velocity of the air stream entering the abatement device

(Wang et al., 2000). The particle size distribution of most aerosols can be described by a log-normal distribution (Hinds, 1999). While they have historically been considered low-efficiency collectors, recent studies have shown that cyclones can reach efficiencies exceeding 99 percent for particles larger than five micrometers (Cooper and Alley, 2002).

The Texas A&M Cyclone Design (TCD) method is a simple method for designing cyclones based on an "optimal" inlet velocity. According to the TCD method, the optimal inlet air speed for a 1D3D cyclone is 975 ± 120 m/min (3200 ± 400 fpm) and 914 ± 120 m/min (3000 ± 400 fpm) for 2D2D cyclones under standard conditions (Parnell, 1996). The air stream velocities specified by the TCD method seek to balance the competing desires for high efficiency and low pressure drop through the abatement device. Further testing has indicated that higher efficiencies than those predicted by the TCD method may be achieved by increasing air speed through the cyclone. However, an increase in exit concentrations has been observed for velocities that are significantly higher or lower than the design velocities. This higher collection efficiency is accompanied by increased pressure drop across the cyclone, thus requiring higher energy inputs. There may be times when it is economically beneficial for a processing industry to incur higher energy costs rather than convert to a filter system, the cost of which may be five to ten times higher than that of a cyclonic abatement system (Parnell, 1996). The objective of the research described in this paper is to characterize the collection efficiency and pressure drop associated with 1D3D and 2D2D cyclones across a range of inlet velocities. A secondary objective is to determine the maximum collection efficiency and associated inlet velocity for 1D3D and 2D2D cyclones with varying loading rates of two dust samples. Additionally, the "optimal" inlet velocities specified by the TCD method will be evaluated based on collection efficiency and operating costs, which are a function of both inlet velocity and pressure drop.

MATERIALS AND METHODS

A three-factorial experiment was conducted for both 1D3D and 2D2D cyclones, varying inlet loading concentration, aerosol PSD, and inlet velocity. Commercially available cornstarch and alumina were used as the test dusts in these trials (Table 1). Cornstarch was used because the PSD of cornstarch is near to that of corn dust from grain elevators. Alumina was also used because a second dust with a relatively low mass median diameter (MMD) was desired. A Beckman Coulter Counter Multisizer™ 3 (Beckman Coulter, Miami, Florida) was used to determine the PSD of each dust. The Coulter Counter is calibrated by the manufacturer annually and by laboratory technicians every 100 runs.

The Coulter Counter measures Equivalent Spherical Diameter (ESD) which is then converted to Aerodynamic Equivalent Diameter (AED) using eq 1:

$$AED = ESD\sqrt{\frac{\rho_p}{\chi}} \tag{1}$$

where: AED = aerodynamic equivalent diameter,

ESD = equivalent spherical diameter,

ρ_p = particle density (g/cm^3), and

χ = shape factor.

The AED of an aerosol particle is the diameter of a unit density sphere (i.e.: density = 1.00 g/cm^3) that would have the same settling velocity as the particle or aerosol in question.

The particle size distribution was described as a log-normal distribution using an MMD and geometric standard deviation (GSD), where MMD is the particle size for which half of the mass is contributed to by particles smaller than the MMD and half by particles larger than the MMD (Hinds, 1999). The GSD is calculated using eq 2:

$$GSD = \sigma_g = \frac{d_{84.1\%}}{d_{50\%}} = \frac{d_{50\%}}{d_{15.9\%}} = \sqrt{\frac{d_{84.1\%}}{d_{15.9\%}}} \quad (2)$$

where $d_{n\%}$ is the particle size for which n percent of the mass is contributed by particles less than d.

Table 1. Properties of experimental aerosols.

Aerosol	Particle Density (g/cm3)	Shape Factor	MMD (AEDa) (µm)	*GSD*
Cornstarch	1.5	1.00	17.95	*1.41*
Alumina	3.9	1.44b	9.96	*1.42*

a. aerodynamic equivalent diameter
b. Source: (Mark et al., 1985)

1D3D and 2D2D metal cyclones with a diameter of 0.1524 m (6 in.) were used to conduct experiments with the pull system shown in Figure 2.

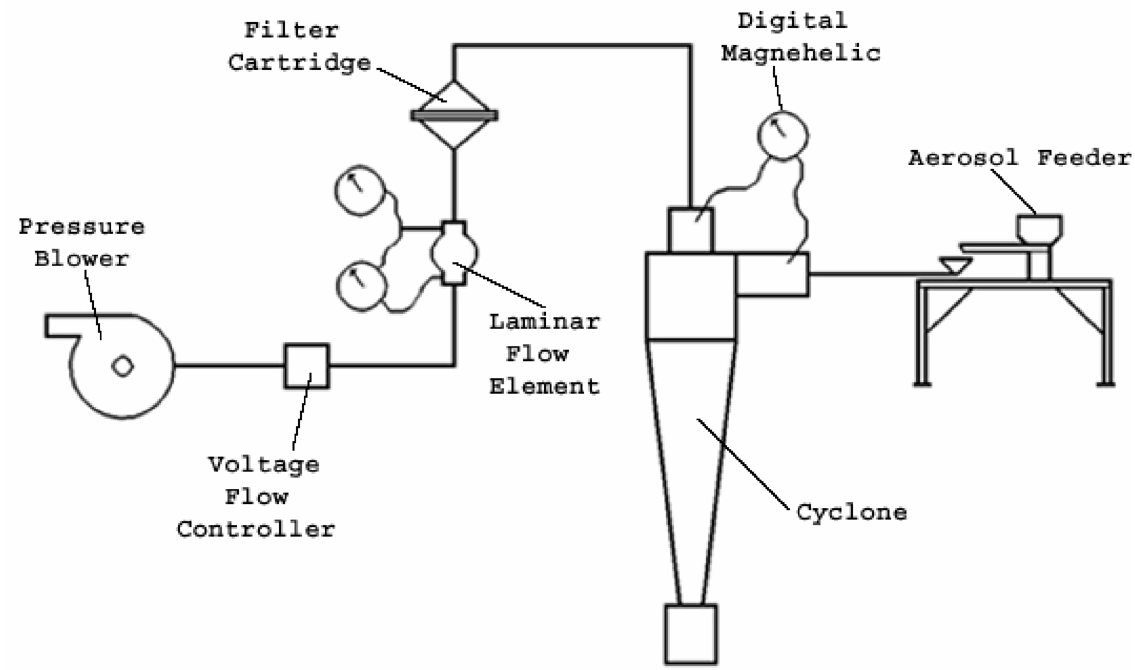


Figure 2. Cyclone testing system for inlet velocity tests.

A laminar flow element (LFE) (Meriam Instrument Model 50MC2-2; Serial No. 773880-NI, Cleveland, Ohio), calibrated by the manufacturer, was used to determine the flow rate of air through the system, and a voltage controller was used to obtain the desired flow rate. The actual flow rate was corrected for air temperature using a correction factor furnished by the LFE manufacturer.

For each test, the temperature, barometric pressure, and relative humidity were recorded. Wang et al. (2003) demonstrated that, for highest efficiency, cyclones should be designed based on inlet velocities of dry-standard air rather than actual conditions. A digital magnehelic (Dwyer Instruments, Series 475 Mark III, Michigan City, Indiana) was used to determine the negative pressure created by the cyclone, filter, and piping upstream of the LFE, and the standard flow rate through the system was calculated. The standard flow rate of air was calculated based on the actual air density and a standard density of 1.20 kg/m^3 (0.075 lb/ft^3) using eq 3:

$$Q_{std} = Q_{act}\frac{\rho_{act}}{\rho_{std}} \tag{3}$$

where: Q_{std} = flow rate of standard air,

Q_{act} = measured flow rate,

ρ_{act} = measured density of air (kg/m^3), and

ρ_{std} = density of standard air (kg/m^3).

For each trial, a filter was placed in the filter holder and the fan was turned on. When equilibrium at the desired flow rate was reached, a measured mass of the aerosol was fed into the system using a vibratory feeder at a specified rate. The feed rate was controlled by adjusting the frequency of vibration and verified by visual inspection. Test durations were three minutes for glass fiber filters (for gravimetric analysis) and ten minutes for Teflon filters (for gravimetric and particle size analysis). Tests were longer for filters used in particle size analysis so that enough dust would accumulate on the filters to run three sets of PSDs. Three minute tests were deemed sufficient for gravimetric analysis because the amount of dust that accumulates on a filter during a three minute test is larger than the measurement variability of the scale used, and preliminary tests demonstrated that the dust collection efficiency of the cyclone is statistically similar ($\alpha < 0.05$) for three and ten minute tests.

Between tests the system was run for three minutes to clear any residual dust out of the system. During each trial, the mass of dust entrained in the system and the test duration were measured and used in conjunction with the volumetric flow rate through the system to determine the loading concentration according to eq 4:

$$C = \frac{m_{in}}{Q * t} \tag{4}$$

where: C = inlet loading concentration (g/m^3),

m_{in} = mass of dust entrained in the system (g),

Q = system flow rate (m^3/s), and

t = test duration (s).

The pressure drop across the cyclone and the laminar flow element were measured using digital magnehelics with a 0.01 kPa resolution (Dwyer Instruments, Series 475 Mark III, Michigan City, Indiana). Teflon filters (with 2µm pore size) were used for replications requiring PSD analysis because of the lower background particle count as compared to glass fiber filters. The background particle count quantifies the number of particles within the size range of interest which are generated from analysis of a blank (unused) filter and are detected during particle size analysis. Evaluation of blank glass fiber filters by Buser (2004) indicated a background concentration of 12,388 particles in 500 µl of electrolyte, while 2-µm Teflon filters yielded only 58 particles in an equal amount of electrolyte. Glass fiber filters were used for the remaining replications requiring only gravimetric analysis as they require less fan power and are significantly less expensive than Teflon filters.

Particle size distributions of the aerosol emitted from the cyclone were obtained by placing ten 1.6-cm diameter samples containing particulates, cut from random locations on a given filter, into a lithium-chloride methanol electrolyte solution and placing this combination into an ultrasonic bath for three minutes. The solution was then filtered through a 100-µm screen to remove large particles. The strained electrolyte/particulate solution was injected into a beaker of electrolyte until a 6-7 percent concentration of dust in the electrolyte was obtained (Herber, 1988). For every PSD analysis in this paper, three replications of three runs each were conducted for all filters and the average used as the reported PSD. Each run measured approximately 300,000 particles.

Initial experiments were conducted for the 1D3D cyclone at nominal inlet velocities of 10.16 m/s, 16.26 m/s, and 20.32 m/s (2000, 3200, and 4000 fpm), at loading rates of 1 and 2 g/m^3, and PSDs analyzed using the Coulter Counter. Loading rates were selected to approximate the loading expected in a process stream at a cotton gin and/or grain elevator. For each combination of inlet velocity and loading rate there were five replications (one using a Teflon filter and four using Glass fiber filters). By conducting experiments at inlet velocities lower than, equal to, and higher than the design velocity specified by Parnell (1996), we established the magnitude of change expected. This allowed for appropriate inlet velocities to be selected for testing. Similar initial tests were conducted for the 2D2D cyclone at inlet velocities of 10.16 m/s, 15.24 m/s, and 20.32 m/s (2000, 3000, and 4000 fpm) at loading rates of 1 and 2 g/m^3.

For both cyclones, subsequent similar tests were run with 1 and 2 g/m^3 loading rates at inlet velocities ranging from 10.16 m/s (2000 fpm) at standard conditions, corresponding to the lowest recommended conveying velocity for seed cotton (Baker et al, 1994), to 20.32 m/s (4000 fpm), 2.04 m/s (400 fpm) above the maximum design velocity of the 1D3D cyclone according to the TCD method.

For gravimetric tests, filters were weighed before and after each trial using a 10-µg resolution scale (AG245, Mettler Toledo, Greifensee Switzerland). In order to reduce uncertainty associated with filter weights, three pre-weights and three post-weights were taken and the averages were used to determine the amount of dust collected on the filter.

The efficiency of cyclonic separation was calculated for each test using the eq 5:

$$\eta = 1 - \frac{\Delta m_{filter}}{m_{in}} x100\% \tag{5}$$

where: η = cyclone efficiency (%),

Δm_{filter} = post-weight of the filter minus the pre-weight of the filter (g), and

m_{in} = mass of dust entrained in the system (g).

An analysis of variance test was conducted on the collection efficiencies of all treatments, and the MMDs and GSDs of all Teflon filters for each treatment. A post hoc Tukey's HSD procedure was conducted to analyze the data. The null hypotheses tested ($\alpha = 0.05$) were that the collection efficiencies of each treatment were equal and the MMD and GSD of emitted aerosols were equal.

A lognormal curve was used to describe the PSD data from each exposed Teflon filter. These characteristic lognormal distributions were subsequently used to determine the fractional efficiency curve (FEC) of the cyclone for each test. A fractional efficiency curve describes the efficiency with which a cyclone separates particles of a given size from the entering aerosol mixture. The cyclone collection efficiency for a given size range was determined using eq 6:

$$\eta_j = \frac{m_{in} * f_{in,j} - m_{filter} * f_{filter,j}}{m_{in} * f_{in,j}} \tag{6}$$

where: η_j = fractional collection efficiency of j^{th} size range,

m_{in} = mass of dust entrained in the entering air stream,

$f_{in,j}$ = fraction of dust entering the cyclone in the j^{th} size range,

m_{filter} = mass of dust deposited on the filter, and

$f_{filter,j}$ = fraction of dust deposited on the filter in the j^{th} size range.

The size distribution of the fractional collection efficiency is the difference between two lognormal distributions (the PSD of dust entrained in the air stream and the PSD of dust collected on the filter) and can also be described using a lognormal distribution. The size range at which 50 percent of the particles are collected is known as the cyclone cut point. The slope of the cyclone collection efficiency curve is described by eq 7:

$$Slope = \frac{d_{84.1\%}}{d_{50\%}} = \frac{d_{50\%}}{d_{15.9\%}} = \sqrt{\frac{d_{84.1\%}}{d_{15.9\%}}} \tag{7}$$

where $d_{n\%}$ is the particle size for which n percent of the particles are collected by the cyclone.

RESULTS AND DISCUSSION

Using fractional efficiency curves, characteristics were determined for the 0.154 m (6 in.) cyclones used in these experiments (Table 2). As expected, the measured cut points of both cyclones were proportional to the MMD of the experimental aerosol.

Table 2. Cyclone characteristics for inlet velocity tests.

Cyclone	Cornstarch			Alumina		
	d50	Slope	MMD/d50	d50	Slope	MMD/d50
1D3D	4.7	1.10	3.8	2.67	1.11	3.7
2D2D	5.0	1.11	3.6	2.49	1.13	4.0

COLLECTION EFFICIENCY

For both the 1D3D and 2D2D cyclones and for both dusts at all tested inlet velocities, no significant difference was detected in cyclone collection efficiency between the inlet loading rates of 1 and 2 g/m^3. For tests in which cornstarch was used as the test aerosol, no significant difference in cyclone efficiency was detected for either the 1D3D (Figure 3) or 2D2D (Figure 4) cyclones for inlet velocities ranging from 10.16 to 20.32 m/s (2000 to 4000 fpm). However, for tests in which alumina was used as the test aerosol, significant differences were detected in the collection efficiencies of both the 1D3D and 2D2D cyclone.

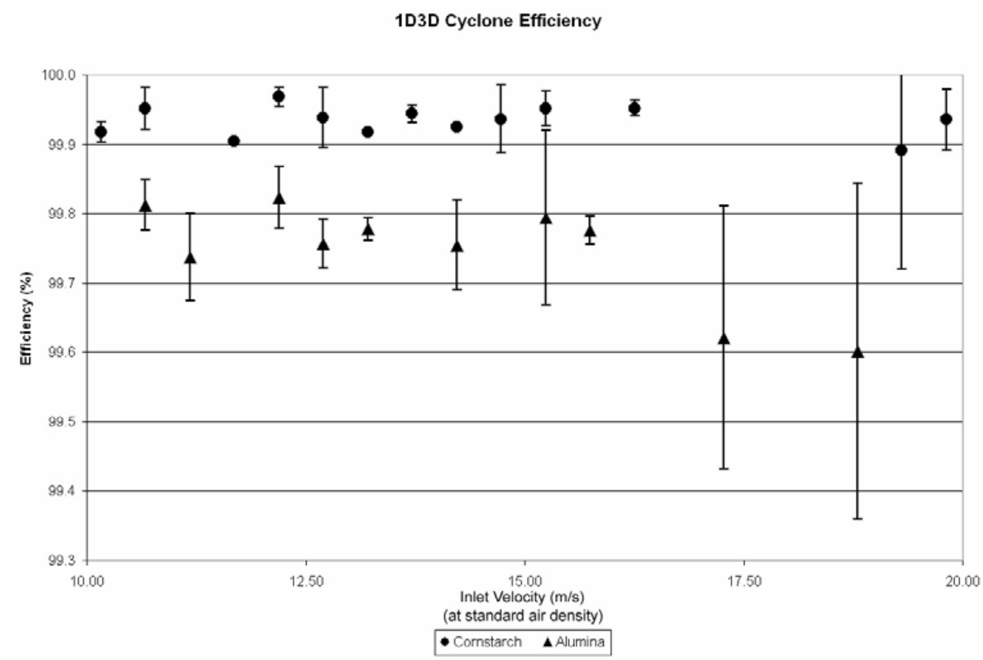


Figure 3. Collection efficiencies with 95% confidence intervals of the 1D3D cyclone for all replications at each inlet velocity and inlet loading rate combination.

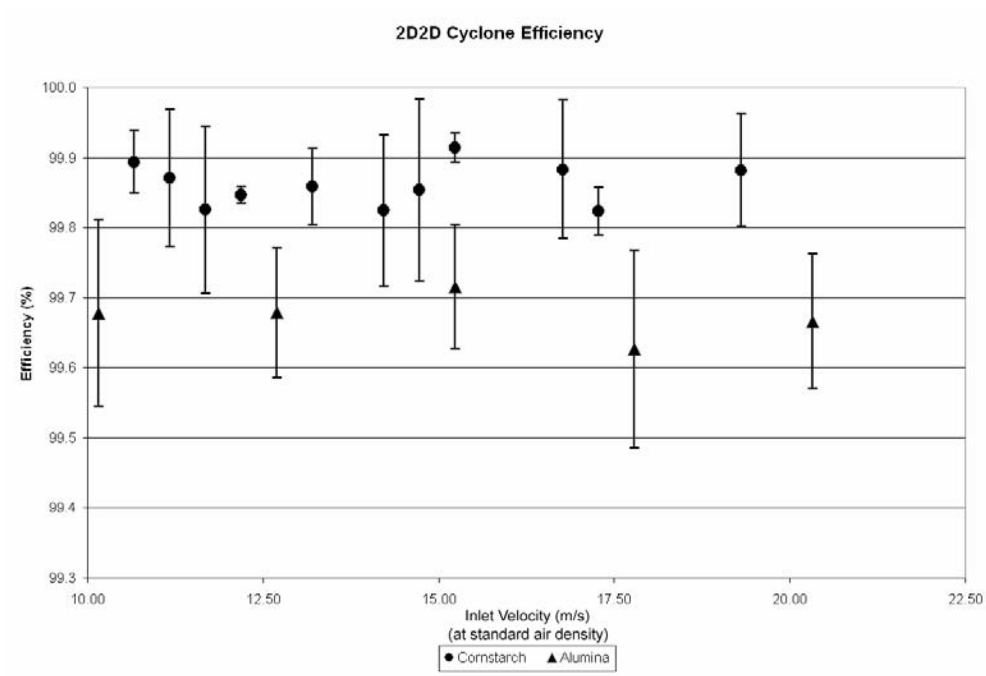


Figure 4. Collection efficiencies with 95% confidence intervals of the 2D2D cyclone for all replications at each inlet velocity and inlet loading rate combination.

Tests of the 1D3D cyclone with alumina (Figure 3) showed that for all inlet velocities between 10.16 and 15.75 m/s (2000 and 3100 fpm) collection efficiencies were not statistically different. However, for inlet velocities greater than 17.27 m/s (3400 fpm), cyclone collection efficiency was significantly lower than that found at 15.24 m/s (3000 fpm).

Tests of the 2D2D cyclone with alumina (Figure 4) showed that the collection efficiency at 17.78 m/s (3500 fpm) was statistically lower than at 15.24 m/s (3000 fpm), at which the highest collection efficiency was observed. However, collection efficiencies were not statistically different for all inlet velocities between 10.16 and 15.24 m/s (2000 and 3000 fpm). The standard deviation of measured collection efficiencies increased as inlet velocity increased above 16.26 m/s (3200 fpm) for the 1D3D cyclone and 15.24 m/s (3000 fpm) for the 2D2D cyclone.

The collection efficiency of cyclonic separators is a function of the aerosol PSD and the inlet velocity of the air stream. These results showed that the collection efficiency was not impacted by loading rate for the loading rates used (less than or equal to 2 g/m^3). All treatments demonstrated collection efficiencies above 99 percent, regardless of the inlet velocity, cyclone, or aerosol being tested.

For aerosols with an MMD greater than 3.5 times larger than the cut point of the cyclone and GSD less than or equal to 1.42, collection efficiencies equal to those obtained using the TCD design inlet velocity may be obtained at lower inlet velocities. However, above the TCD design inlet velocity, the variability of collection efficiency increases. This increased variability is due to increased turbulence and disruption of the vortex within the cyclone. Further research is needed to determine the lowest MMD to cut point ratio for which this relationship holds.

PRESSURE DROP

The pressure drop across the cyclone is directly related to the fan power required to operate a cyclonic abatement device. Therefore, it is important that the pressure drop associated with each inlet velocity be measured so that an estimate of the operating cost at each inlet velocity may be obtained. The pressure drops for each replication as measured across the 1D3D and 2D2D cyclones are shown in Figures 5 and 6, respectively:

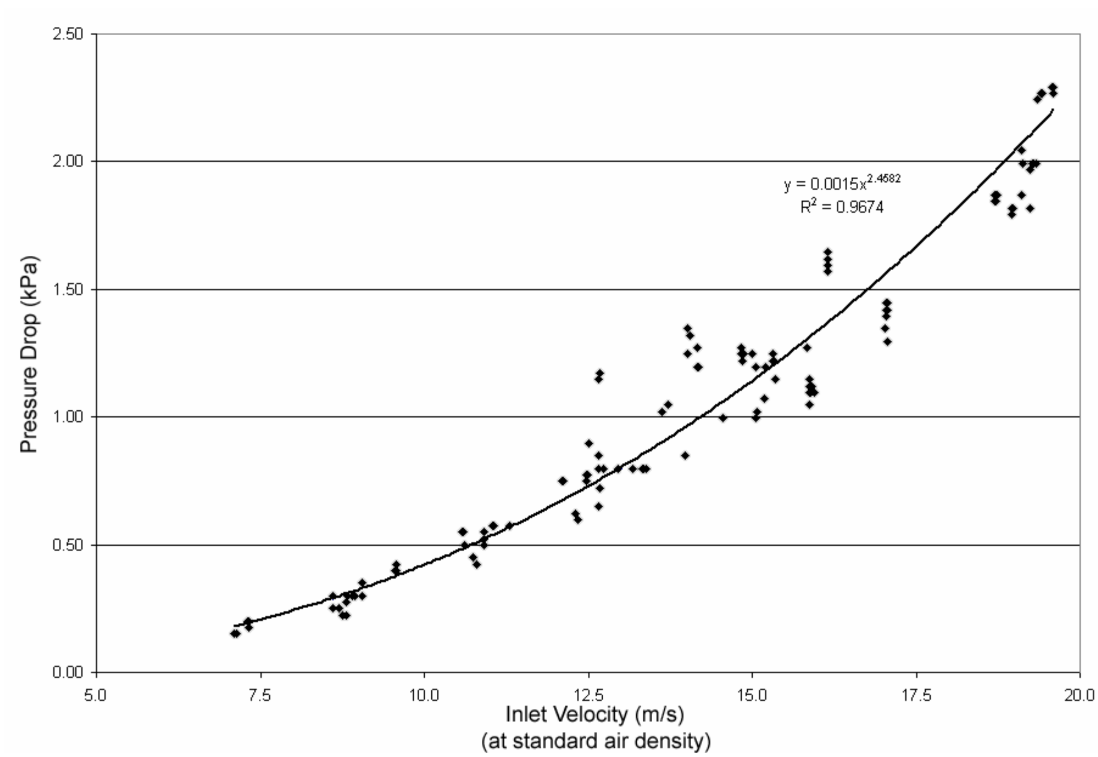


Figure 5. Pressure drop measured across the 1D3D cyclone for all replications at each inlet velocity.

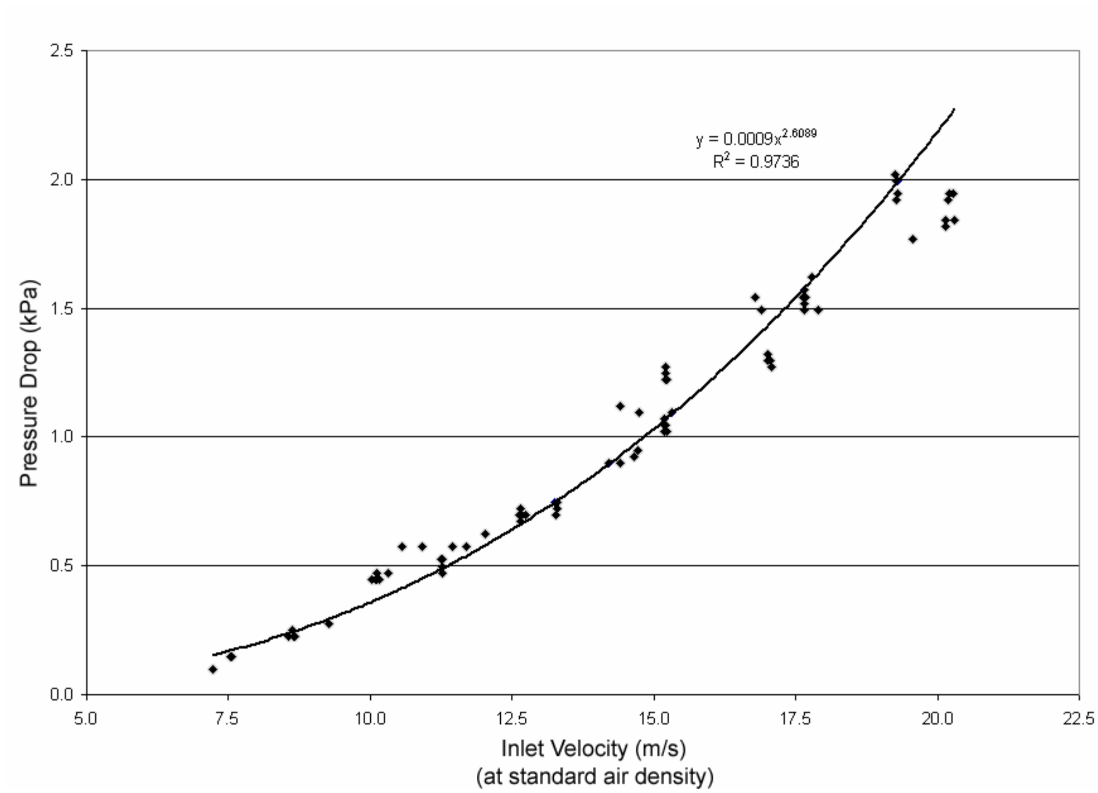


Figure 6. Pressure drop measured across the 2D2D cyclone for all replications at each inlet velocity.

As expected, the pressure drop through both the 1D3D and 2D2D cyclones increased as inlet velocity increased (Figures 5 and 6). However, the experimentally observed pressure drop was higher than that predicted by the TCD method for both cyclones. Given the wide range over which collection efficiencies were equal, it is desirable to operate at the lowest flow rate possible for which the collection efficiency of the cyclone is acceptable in order to reduce operating costs of the abatement device.

Based on the TCD method, 1D3D and 2D2D cyclones should operate at inlet velocities of 975 ± 120 m/min (3200 ± 400 fpm) and 914 ± 120 m/min (3000 ± 400 fpm), respectively. The results of this research indicate that collection efficiencies similar to those obtained at the TCD design inlet velocity may be obtained at lower inlet velocities when separating aerosols with MMDs that are much larger than the cyclone cut point. This reduction in inlet velocity is accompanied by a reduction in the pressure drop across the cyclone, resulting in lower required energy requirements. The potential energy savings that result from operating a 0.457 m (18 in.) 1D3D and 2D2D cyclone below the TCD design inlet velocity are shown in Table 3. These figures represent the energy savings only through the cyclone and disregard the remainder of the system.

Table 3. Potential energy savings by using lower inlet velocities.

Cyclone	Inlet Velocity (m/s)	Flow Rate (m3/s)	Pressure Drop (kPa)	Energy (kW)	% Energy Use v. TCD*
1D3D	16.26	0.0425	1.03	0.44	100%
	13.21	0.0345	0.62	0.22	49%
	10.16	0.0265	0.32	0.09	20%
2D2D	15.24	0.0398	1.18	0.47	100%
	12.70	0.0332	0.73	0.24	52%
	10.16	0.0265	0.41	0.10	23%

* TCD = Texas A&M Cyclone Design

CONCLUSIONS

When separating large aerosols from process air streams, cyclones may be operated at inlet velocities well below the TCD design specifications. The results of this research show that agricultural processing industries such as cotton gins and grain elevators can operate cyclones at lower inlet velocities and easily obtain collection efficiencies equal to those predicted by the TCD method. These findings make it much less critical for these industries to maintain the narrow window of flow rates specified by the TCD method in order to be in regulatory compliance with federal and state permit guidelines. All treatments demonstrated collection efficiencies above 99 percent for the tested aerosols, regardless of the inlet velocity or cyclone. Further research is needed to determine how the results of these tests may be scaled to larger diameter cyclones.

CHAPTER III

EFFECTS OF CYCLONE DIAMETER ON PERFORMANCE OF 1D3D CYCLONES: COLLECTION EFFICIENCY

OVERVIEW

Cyclones are the most commonly used air pollution abatement device for separating particulate matter (PM) from air streams in agricultural processes such as cotton gins. Several models have been proposed to predict the performance of cyclones as diameter varies. This paper presents the results of a collection efficiency test using 15.24, 30.48, 60.96, and 91.44 cm (6, 12, 24, and 36 inch) diameter cyclones with poly-disperse PM having an aerodynamic mass median diameter near ten microns. The mass of PM collected by the cyclones and the mass of PM that penetrated the cyclones and was deposited on a set of filters was used to determine the collection efficiency of each cyclone. The collection efficiency of cyclones decreased as cyclone diameter increased. The objective of this research was to develop a model to accurately characterize the change in cyclone performance with changes in cyclone diameter based on empirical data.

INTRODUCTION

Cyclones are the most commonly used air pollution abatement device for separating particulate matter (PM) from air streams in agricultural processes. Cyclones are relatively inexpensive to install and operate and have no moving parts, thus minimizing maintenance requirements. An air stream containing PM enters a cyclone tangentially near the top of the cyclone and spirals downward. Inertial and centrifugal forces move the particulates outward to the wall of the cyclone where the PM slides down to the trash outlet at the bottom of the cone section and is removed.

Cyclone performance is a function of the geometry and operating parameters of the cyclone, as well as the particle size distribution (PSD) of the entrained PM (Wang et al., 2000). Several mathematical models have been proposed to predict cyclone performance. Lapple (1951) developed a semi-empirical relationship to predict the cut point of cyclones designed according to the Classical Cyclone Design method, where the cyclone cut point is defined as the particle diameter corresponding to 50% collection efficiency. However, Lapple's approach does not account for the effects of PSD on cyclone performance, documented by Wang et al. (2000).

The Lapple (1951) model is based on the terminal velocity of particles in a cyclone. From the theoretical analysis, equation 8 is derived to determine the smallest particle that will be collected by a cyclone if it enters at the inside edge of the inlet duct:

$$d_p = \sqrt{\frac{9\mu W}{\pi N_e V_i \left(\rho_p - \rho_g\right)}} \tag{8}$$

where: d_p = diameter of the smallest particle that will be collected by the cyclone if it enters on the inside edge of the inlet duct (μm),

μ = gas viscosity (kg/m-s),

W = width of inlet duct (m),

N_e = number of turns of the air stream in the cyclone,

V_i = gas inlet velocity (m/s),

ρ_p = particle density (kg/m^3), and

ρ_g = gas density (kg/m^3).

Theoretically 100% of particles of size d_p would be collected. Assuming Stoke's regime flow holds in cyclones, it would be expected that that the cut point of any cyclone would be modeled by multiplying a constant, C, by the particle diameter calculated using equation 8 (equation 9):

$$d_{pc} = C\sqrt{\frac{9\mu W}{\pi N_e V_i\left(\rho_p - \rho_g\right)}} \tag{9}$$

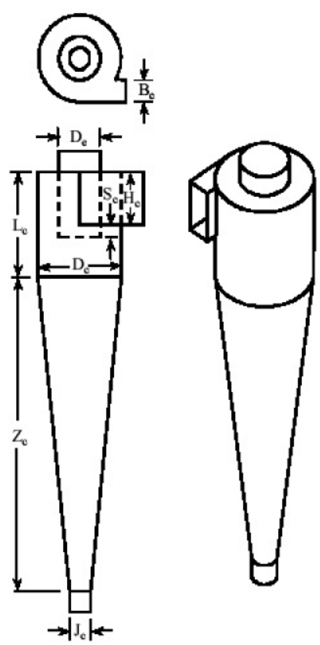
Lapple (1951) determined that the value of C is equivalent to 0.7071, predicting that cyclone cut point can be calculated using equation 10:

$$d_{pc} = \sqrt{\frac{9\mu W}{2\pi N_e V_i\left(\rho_p - \rho_g\right)}} \tag{10}$$

where d_{pc} is the cyclone cut point.

Several other mathematical models have also been proposed, including that by Pant et al. (2002), which was empirically developed to predict the effects of changing cyclone geometric parameters. Their model was intended for application with "miniature" cyclones, but the limits of the model's applicability were not clearly stated. Barth (1956) developed a model to predict cyclone cut point based on force balance as a function of volumetric flow rate, effective cyclone length, and inlet velocity. Barth's model was subsequently corrected by Wang, et al (2003) to more closely match experimental data taken using 15.24 cm (6 inch) diameter 1D3D and 2D2D cyclones.

The Texas A&M Cyclone Design (TCD) method specifies cyclone dimensions based on a the diameter (D_c) of the cyclone barrel (Figure 7). The barrel diameter is selected so that the volumetric flow rate of air (determined by the application) through the inlet cross-section ($D_c/2 \times D_c/4$) results in the TCD design inlet velocity (975 ± 120 m/min [3200 ± 400 fpm] for 1D3D cyclones). The Ds in the 1D3D designation refer to the diameter of the cyclone barrel, while the numbers preceding the Ds refer to the relative length of the barrel and cone sections, respectively. Therefore, a 1D3D cyclone has a barrel length equal to the barrel diameter and a cone length equal to three times the barrel diameter.



$B_c = D_c/4$ $H_c = D_c/2$ $S_c = D_c/8$
$D_e = D_c/2$ $J_c = D_c/3$ $L_c = 1*D_c$
$Z_c = 3*D_c$

Figure 7. 1D3D cyclone configuration.

Each of the aforementioned models: Lapple (1951), Pant et al. (2002), and Barth (1956) were used to predict the cut point of 1D3D cyclones ranging in size from 10.16 to 152.4 cm (4 to 60 inches) in diameter [using air viscosity = 1.85×10^{-5} Pa-s; inlet velocity = 975 m/min; particle specific gravity = 3.9; gas density = 1.18 kg/m^3]. The results of all models predicted an increase in cut point as cyclone diameter increased. The predicted cut points increase according to the equation:

$$d_{50} = ax^b \tag{11}$$

where: d_{50} = cyclone cut point (μm),

x = cyclone diameter (cm), and

a and b = curve-fit coefficients.

The values of a and b for each model are shown in Table 4. All R^2 values equal to 1.00.

Table 4. Constant values for equation 11 predicted by mathematical models.

Model	a	b
Lapple	0.4412	0.488
Pant, et al	0.6242	0.5767
Barth	0.7305	0.4963

Another simplified model of a given particle's path through a cyclone was used where the particle followed the center of a laminar air stream through the course of the cyclone. Using this simplified model, the total energy imparted to a particle in a cyclone was calculated according to equation 12:

$$E = \int_0^d F dx \tag{12}$$

where: E = energy imparted to the particle (J),

F = force acting on the particle (N),

x = distance traveled by the particle (m), and

d = total path length of a particle through the cyclone (m).

The velocity and travel distance of the air stream within the cyclone were calculated according to the approach outlined by Wang et al. (2001). According to this approach, the tangential velocity of the air stream in the barrel portion of the cyclone is equal to the inlet velocity, and the travel distance in the cyclone barrel is determined by equation 13:

$$L_b = N_b \pi D_c \tag{13}$$

where: L_b = travel distance in the cyclone barrel (m),

N_b = turns in the cyclone barrel [1.53 for 1D3D cyclones (Wang, et al, 2001)], and

D_c = cyclone barrel diameter (m).

In the cone section of a cyclone, the air stream velocity increases as the cross-sectional area of the cyclone decreases. The tangential velocity in the cone portion of a 1D3D cyclone at time t is described according to equation 14:

$$V_{t,c} = \frac{4D_c * V_{in}}{Z + 2D_c} \tag{14}$$

where: $V_{t,c}$ = tangential velocity at time t in the cyclone cone (m/s),

D_c = cyclone barrel diameter (m),

V_{in} = inlet velocity (m/s), and

Z = travel distance in the axial direction at time t (m).

Based on these equations, the centrifugal force acting on a particle was calculated according to equation 15:

$$F = m\frac{v^2}{r} \tag{15}$$

where: F = force acting on the particle (N),

m = mass of particle (kg),

v = tangential velocity (m/s), and

r = radius of the particle's path (m).

The distance traveled in the axial direction at time t can be found using equation 16, assuming that Z is equal to zero when t is equal to zero.

$$Z = \int_0^t \frac{4D_c * V_{in}}{(Z + 4D_c)\pi} t \tag{16}$$

where: Z = travel distance in the axial direction at time t (m),

D_c = cyclone barrel diameter (m),

V_{in} = inlet velocity (m/s), and

t = time (s).

Integrating the centrifugal force over the distance traveled (eq. 6), the diameter terms were reduced such that the amount of energy imparted on the particle in the cyclone did not change, regardless of the cyclone diameter. This model is referred to as the energy dissipation model and implies that, given fixed geometric proportions and inlet velocity, the cut point of a cyclone should not be a function of cyclone diameter.

The cut points of a 1D3D cyclone operating with an inlet velocity of 975 m/min (3200 fpm) predicted using each of the aforementioned models are shown in Figure 8.

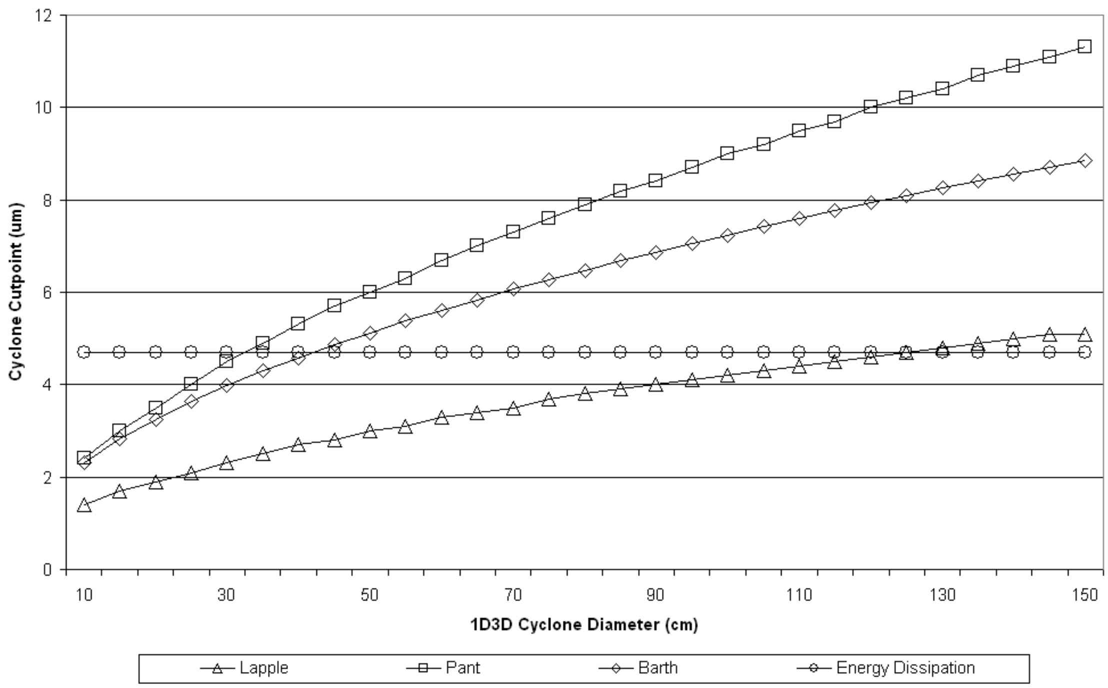


Figure 8. 1D3D cyclone cut point models.

An accurate assessment of the change in cyclone cut point with changes in barrel diameter is important when designing or evaluating the efficiency of cyclones as PM abatement systems. Given PM with a consistent PSD, the total collection efficiency of a cyclone will increase as the cut point decreases. If cut point is a function of cyclone diameter, there may be significant benefits in utilizing smaller diameter cyclones to reduce PM emissions from process streams. The objective of this research is to characterize the change in cyclone performance with changes in cyclone diameter.

MATERIALS AND METHODS

To determine the relationship between cyclone barrel diameter and cut point, four 1D3D cyclones (15.24-, 30.48-, 60.96-, and 91.44-cm [6-, 12-, 24-, and 36-inch] diameter] were evaluated based on collection efficiency. The system used for testing is shown in Figure 9.

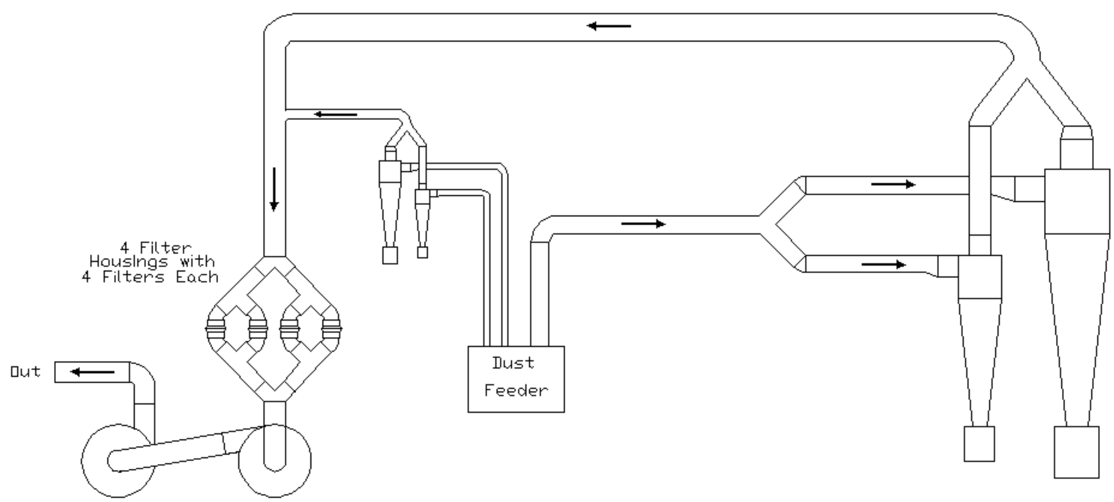


Figure 9. Cyclone testing system for similitude tests.

According to the Texas A&M Cyclone Design method, 1D3D cyclones should be operated with an inlet velocity of 975 ± 120 m/min (3200 ± 400 fpm) in order to balance the desire for maximum collection efficiency with the need for low pressure drop through the abatement device (Parnell, 1996). However, there is some debate as to whether the inlet velocity should be measured in actual or standard terms. Therefore, where possible, tests were conducted using both actual and standard inlet velocities. The standard flow rate of air was calculated based upon a standard air density of 1.20 kg/m^3 (0.075 lb/ft^3) using equation 17:

$$Q_{std} = Q_{act} \frac{\rho_{act}}{\rho_{std}} \tag{17}$$

where: Q_{std} = flow rate of standard air,

Q_{act} = measured flow rate,

ρ_{act} = measured density of air (kg/m^3), and

ρ_{std} = density of standard air (kg/m^3).

Due to fan limitations, it was not possible to test the 91.44 cm (36 inch) diameter cyclone using standard inlet velocities.

Before each test, the system was run with no filters for several minutes to clean out any residual PM in the ducts. Microalumina (mass median diameter [MMD] = 10.3-μm aerodynamic equivalent diameter [AED] and geometric standard deviation [GSD] = 1.40, Figure 10) was fed into the cyclone at a rate of 3 g/m^3. An AccuFeeder vibratory screw feeder (VibraScrew, Inc.; Totowa, NJ) was used to meter the PM into the system, and the feed rate was verified by weighing the feeder before and after each test to the nearest 0.01 lb.

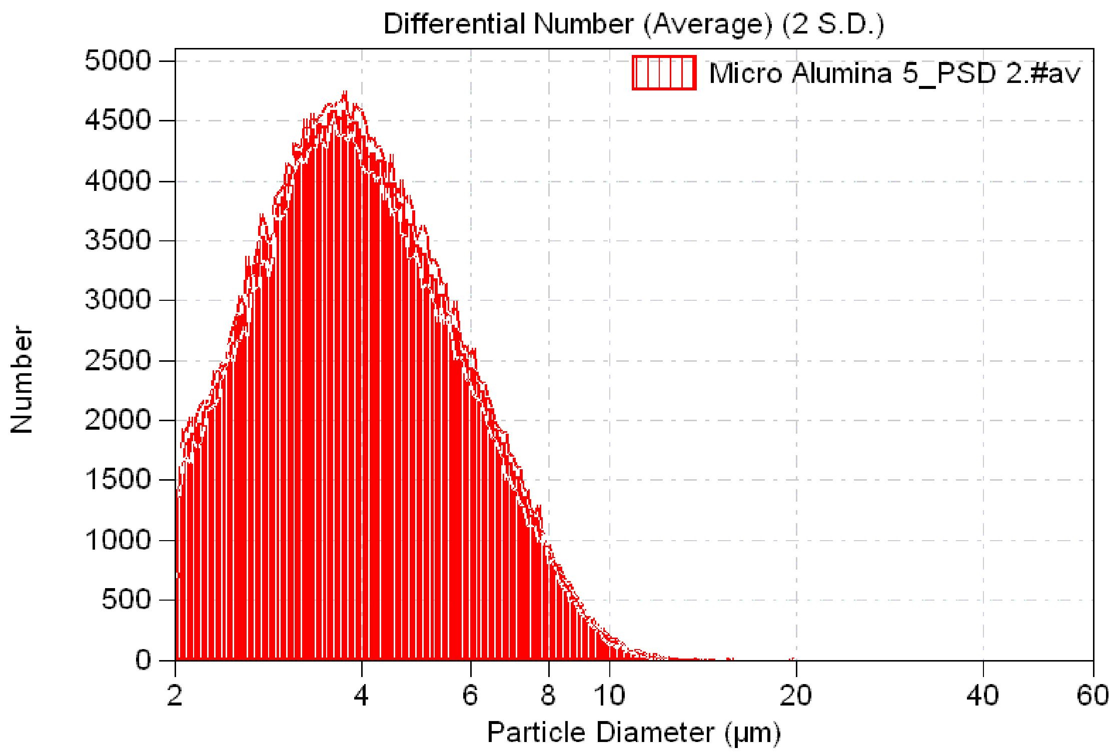


Figure 10. Particle size distribution of microalumina (in equivalent spherical diameter).

Tests were conducted for 30 minutes for the 15.24, 30.48, and 60.96-cm (6, 12, and 24 inch) diameter cyclones. This time period was selected in an effort to minimize the startup and stopping effects associated with the tests. The duration of tests for the 91.44 cm (36 inch) diameter cyclone was limited because the static pressure drop across the filters increased rapidly as the PM that penetrated the cyclone was deposited on the filter. The 91.44 cm (36 inch) diameter cyclone tests were run until the system flow rate fell to such a point that the cyclone inlet velocity was 853.2 actual m/min (2800 afpm). Baffles on the exhaust side of the fans were used to adjust the system flow rate to compensate for reduced flow that occurred as the filters were loaded.

The PM captured by the cyclone was collected in a sealed container, and, for each run, the mass of PM collected was determined using an A&D model HP-20K scale with a 0.1 g resolution. PM that penetrated the cyclone was collected on 16 – 20.32x25.40 cm (8x10") glass fiber filters. The filters were conditioned for a minimum of 48 hours in an environmental chamber at 21.1°C (70°F) and 35% relative humidity. The filters were weighed before and after the test runs to determine the mass of PM that penetrated the cyclone. Each filter was weighed to the nearest 10μg three times before and after the test using an AG-285 (Mettler Toledo) scale. If the standard deviation of the three runs exceeded 50 micrograms then the filters were re-weighed. If the standard deviation of the filter weights was within the allowable tolerance, the three weights were averaged.

Tests were conducted in a randomized block design with replication as the blocking factor. All 11 tests in Table 5 were run, in random order, within each block. The blocks were replicated five times for a total of 55 runs. Within each block, blanks were run for all cyclones in which the cyclones were operated as previously described, except no PM was fed. The purpose of the blanks was to correct for the residual PM in the system from previous runs that may have dislodged and collected on the filters. Blanks were run for 30 minutes for the 15.24, 30.48, and 60.96-cm (6, 12, and 24 inch) diameter cyclones. For the 91.44 cm (36 inch) cyclone, the blank test was run for the same duration as the test with PM in the same block. The mass of PM collected on the filters and in the trash barrels during the blank tests were intended for use as background values for the equivalent size cyclone tests in the same block.

Table 5. Summary of treatments tested within each block.

Cyclone Diameter	Inlet Velocity	Loading Rate
15.24 cm (6 inches)	975 actual m/min (3200 afpm)	0 g/m^3 (blank)
15.24 cm (6 inches)	975 actual m/min (3200 afpm)	3 g/m^3
15.24 cm (6 inches)	975 standard m/min (3200 sfpm)	3g/m^3
30.48 cm (12 inches)	975 actual m/min (3200 afpm)	0 g/m^3 (blank)
30.48 cm (12 inches)	975 actual m/min (3200 afpm)	3 g/m^3
30.48 cm (12 inches)	975 standard m/min (3200 sfpm)	3g/m^3
60.96 cm (24 inches)	975 actual m/min (3200 afpm)	0 g/m^3 (blank)
60.96 cm (24 inches)	975 actual m/min (3200 afpm)	3 g/m^3
60.96 cm (24 inches)	975 standard m/min (3200 sfpm)	3g/m^3
91.44 cm (36 inches)	975 actual m/min (3200 afpm)	0 g/m^3 (blank)
91.44 cm (36 inches)	975 actual m/min (3200 afpm)	3 g/m^3

The collection efficiency of the cyclone was calculated for each trial using equation 18:

$$\eta = \frac{m_{trash}}{m_{trash} + m_{filter}} x100\% \tag{18}$$

where: η = collection efficiency of the cyclone (%),

m_{trash} = mass of PM collected in the trash bin of the cyclone (g), and

m_{filter} = mass of PM collected on the filter (g).

Static pressures were measured throughout the system during testing to ensure that the system functioned properly and to monitor the static pressure loss associated with different cyclone sizes.

RESULTS AND DISCUSSION

The cyclone inlet velocity was determined by measuring the velocity pressure upwind of the cyclone prior to PM being fed into the system. This inlet velocity was correlated to the system flow rate measured downwind of the fans, and any change in flow rate during the tests was assumed to correlate to a change in the cyclone inlet velocity. The average inlet velocity for all cyclones run at actual conditions was 922 actual m/min (3024 afpm) [standard deviation = 41 m/min (134 fpm)]. The average inlet velocity for all cyclones run at standard conditions was 931 standard m/min (3056 sfpm) [standard deviation = 23 m/min (75 fpm)]. The inlet velocities of all runs were within the range of the specified TCD method inlet velocity [i.e. all runs at actual conditions were between 853 and 1097 actual m/min (2800 and 3600 afpm); all runs at standard conditions were between 853 and 1097 standard m/min (2800 and 3600 sfpm)].

The static pressure drop across the cyclones demonstrated no correlation to cyclone diameter. The average static pressure drop across all cyclones was 0.74 kPa (3.0 in. H_2O) with a standard deviation of 0.11 kPa (0.5 in H_2O). This pressure drop was only 70% of the pressure drop predicted using the TCD method.

When the mass of PM deposited on the filters and in the trash barrels of the blank runs was subtracted from the mass of PM deposited on the filters and in the trash barrels of runs with PM, the variability of the data increased. Therefore, the blank tests were not used to normalize the data for statistical analysis. However, the results of the blank tests do indicate the level of systematic uncertainty. The average mass of dust collected on all blank filters was 1727 mg (standard deviation = 3128 mg).

An analysis of variance test was conducted on the collection efficiencies of all treatments. A two-tailed post hoc Tukey's HSD procedure was used with a null hypothesis ($\alpha = 0.05$) that the collection efficiency of each treatment was equal. For each cyclone diameter, no difference was detected between trials run at actual conditions and standard conditions. Therefore all subsequent analyses were conducted only by cyclone diameter and not by inlet velocity treatment.

The collection efficiency of each cyclone size is shown in Table 6. Results with the same letter indicate no statistical difference ($\alpha = 0.05$).

Table 6. Cyclone collection efficiencies for conditions tested.

Cyclone Diameter	Collection Efficiency (%)
15.24 cm (6 inches)	99.49[a]
30.48 cm (12 inches)	99.17[a]
60.96 cm (24 inches)	97.86[b]
91.44 cm (36 inches)	94.52[c]

A regression analysis was also conducted to determine the relationship between cyclone diameter and collection efficiency for the conditions tested. A quadratic curve fit was applied using SPSS (Figure 11).

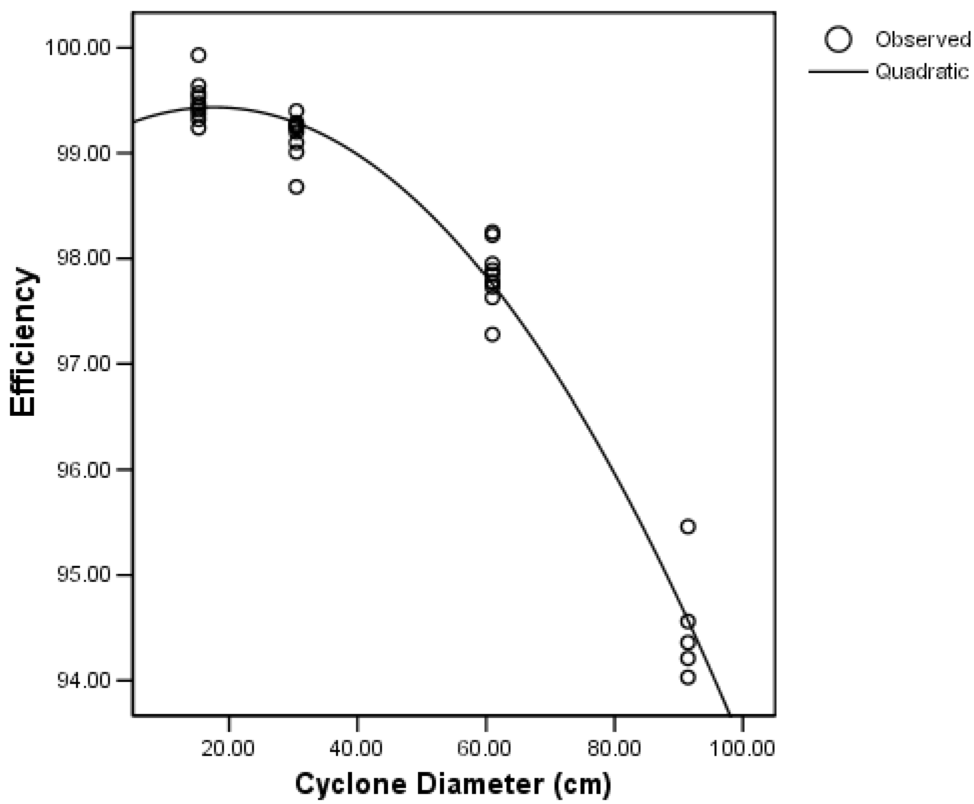


Figure 11. Regression of collection efficiency versus cyclone diameter for conditions tested.

The resulting regression ($R^2 = 0.97$; $\alpha < 0.0005$) can be described by equation 19:

$$\eta = -0.0009d^2 + 0.314d + 99.1587 \tag{19}$$

where: η = cyclone collection efficiency (%) and

d = cyclone diameter (cm).

The cyclone collection efficiency predicted by the aforementioned mathematical models when collecting PM with the same PSD as the microalumina used in this test as are shown in Figure 12.

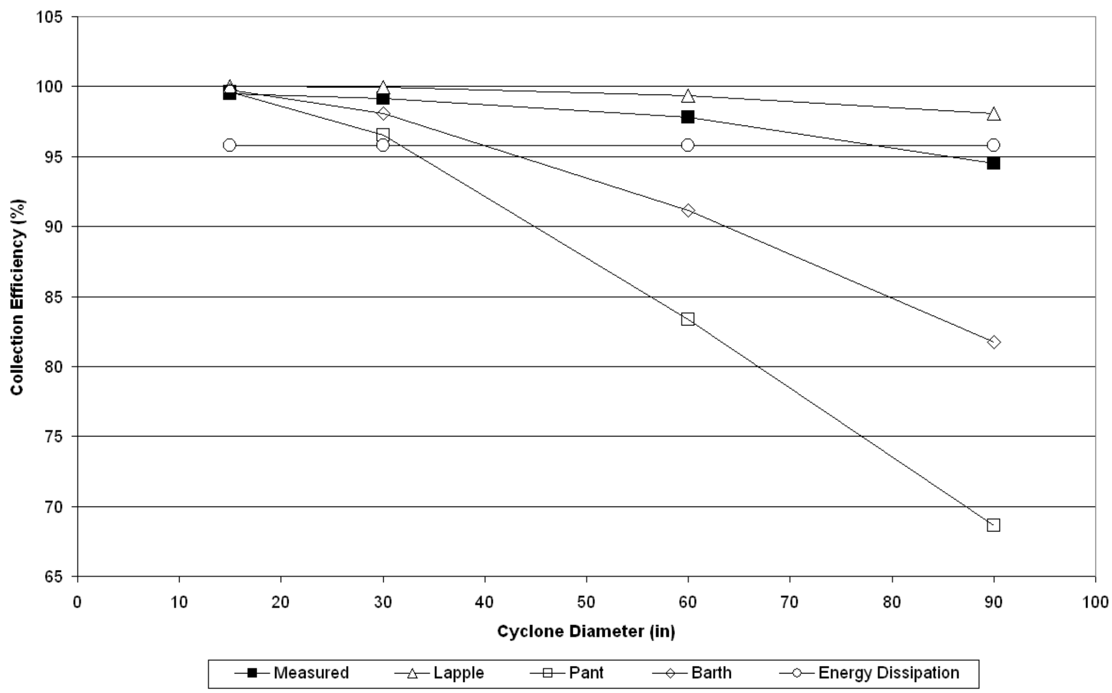


Figure 12. Modeled versus measured collection efficiencies.

Conclusions

The collection efficiency of 15.24, 30.48, 60.96, and 91.44 cm (6, 12, 24, and 36 inch) diameter 1D3D cyclones operated with similar inlet velocities were compared. The collection efficiency decreased as cyclone diameter increased, with statistically significant ($\alpha = 0.05$) differences found between the 30.48, 60.96, and 91.44 cm (12, 24, and 36 inch) diameter cyclones.

None of the mathematical models analyzed in this study accurately predicted the performance of the 1D3D cyclones. The Lapple model slightly over-predicted measured performance, while the Pant and Barth models under-predicted collection efficiency. In future work, the data from this study will be used to develop a new mathematical model to relate cut point to cyclone diameter.

A proper understanding of the relationship between cyclone diameter and performance is important for the design of air pollution abatement systems in order to accurately predict the abatement efficiency. Further analysis (both engineering and economic) should be done to determine the impact changes in cyclone performance with diameter will have on the use of cyclones in industrial applications.

CHAPTER IV

CONCLUSIONS

Cyclones represent a viable and economical option for collecting PM from processing streams in agricultural industries. For PM characterized by relatively large MMDs such as that in cotton gins and grain elevators, cyclones have proven to be efficient collectors over a wide range of inlet velocities ranging from 610 to 1219 m/min (2000 to 4000 fpm). While the collection efficiency of cyclones is inversely related to the barrel diameter, 1D3D cyclones up to 91.44 cm (36 inches) in barrel diameter demonstrated collection efficiencies over 94% when separating PM with an MMD of around 10 micrometers from an air stream. Furthermore, measured static pressure drops across all cyclones tested during this research indicated lower pressure drops than those predicted by the TCD method, indicating that operational costs of using cyclonic abatement devices may be even lower than previously thought. This high collection efficiency combined with low operational and maintenance costs make cyclones an attractive option for agricultural industries that are being ever more hard pressed to reduce emissions of PM to the ambient air.

The aforementioned research indicates that, when separating large aerosols from process air streams, cyclones may be operated at inlet velocities well below the TCD design specifications and still easily obtain collection efficiencies equal to those predicted by the TCD method. Furthermore, it was shown that smaller diameter cyclones are better able to separate smaller particles from air streams than are larger diameter cyclones. However, given the relatively large size of PM emitted from agricultural operations, cyclones with diameters as large as 91.44 cm (36 inches) are able to achieve high collection efficiencies in such applications

FUTURE WORK

While this research has shed significant light on the robust nature of cyclones, much remains to be discovered. Further testing should be conducted to determine the particle size range for which cyclones are able to be operated at low inlet velocities without compromising collection efficiency. An economic analysis should also be conducted to determine whether it would benefit those industries currently utilizing cyclones as PM abatement devices to install larger cyclones that would operate at lower inlet velocities than those currently in use or to add additional cyclones in parallel with those already in use (which would decrease the flow rate and therefore inlet velocity of each cyclone) in order to reduce operating costs.

With regards to similitude, additional analysis of the PSD of dust that was collected by the cyclones as well as that which penetrated the cyclones during testing should be conducted to characterize how cyclone cut point and slope change with size. Furthermore, testing should be conducted using higher capacity fans and/or source sampling to characterize the performance of cyclones at or above 91.44 cm (36 inches) in diameter so that the relationship between cyclone diameter and performance may be refined. It also appears that the current mathematical models used to predict cyclone performance with scale need to be refined to more closely match empirical data.

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APPENDIX A

PUBLICATION STATUS OF MANUSCRIPTS USED IN THIS THESIS

The manuscript entitled "Efficiency and Pressure Drop of Cyclones Across a Range of Inlet Velocities" (Chapter II) has been published in volume 22 of the journal: *Applied Engineering in Agriculture* (January 2006).

The manuscript entitled "Effects of Cyclone Diameter on Performance of 1D3D Cyclones: Collection Efficiency" (Chapter III) will be submitted to the journal: *Applied Engineering in Agriculture* for publication in the near future.

APPENDIX B

WEIGHING PROCEDURE FOR FILTERS

The collection efficiency of cyclones in Chapter II was determined according to equation C1:

$$\eta = 1 - \frac{m_{in}}{\Delta m_f} x100\% \tag{C1}$$

where: η = cyclone efficiency (%),

m_{in} = mass of aerosol entrained in cyclone inlet stream (g), and

Δm_f = change in weight of filter on cyclone exhaust stream (g).

In Chapter III, the collection efficiency of the cyclone was determined according to equation C2:

$$\eta = \frac{m_{trash}}{m_{trash} + m_{filter}} x100\% \tag{C2}$$

where: η = collection efficiency of the cyclone (%),

m_{trash} = mass of PM collected in the trash bin of the cyclone (g), and

m_{filter} = mass of PM collected on the filter (g).

Every filter was numbered and placed in an anti-static shielding bag to prevent contamination of the filter before use. The filter and the bag were labeled with corresponding numbers. After a filter was used, it was placed back into the antistatic bag from which it was originally taken. In both studies, each filter was weighed to the nearest 10μg three times before and after the test using a microbalance. If the standard deviation of the three weights exceeded 50 micrograms then the filters were re-weighed. If the standard deviation of the filter weights was within the allowable tolerance, the three weights were averaged. The difference between the average pre- and post- weights of each filter was used as the mass of PM collected on the filter.

APPENDIX C

UNCERTAINTY ANALYSIS FOR CYCLONE INLET VELOCITY TESTS

Using the method of uncertainty estimation analyzed by Kline and McClintock (1953), the impact of potential errors in each of the primary measurements used to determine the inlet velocity and collection efficiency of cyclones over a range of inlet velocities was determined. This method, commonly known as the propagation of uncertainty, involves using a first or second order Taylor series approximation to estimate the total uncertainty associated with a measurement. This overall uncertainty results from uncertainty in the measurement of each independent variable propagating through data reduction equations (Coleman and Steele, 1999). The following method, used to estimate the systematic uncertainty in both the collection efficiency and standard inlet velocity for each cyclone test, is in accordance with the International Organization for Standardization (ISO) "Guide to the Expression of Uncertainty in Measurement" (ANSI/ASME, 1998).

Assuming that each uncertainty is at the same confidence level (e.g., 95%), let Y be a function of independent variables $x_1, x_2, x_3, \ldots, x_n$, such that the data reduction equation for determining Y from each x_i is:

$$Y = Y(x_1, x_2, x_3, \ldots, x_n) \tag{C1}$$

Then, let ω_i represent the uncertainty of the independent variable x_i, where i ranges between 1 and n. The uncertainty of Y (ω_Y) resulting from the propagation of the uncertainties in each independent variable (x_i) in the data reduction equation can be calculated as the positive square root of the estimated variance, ω_Y^2, from the equation C2 (Holman, 2001):

$$\omega_Y = +\sqrt{\omega_Y^2} \tag{C2}$$

The variance (ω_Y^2) is calculated using equation C3:

$$\omega_Y^2 = \left(\frac{\partial Y}{\partial x_1}\omega_1\right)^2 + \left(\frac{\partial Y}{\partial x_2}\omega_2\right)^2 + \ldots + \left(\frac{\partial Y}{\partial x_n}\omega_n\right)^2 \quad \text{(C3)}$$

The sensitivity coefficient expresses the ratio of the change of the result to a unit change in one input parameter:

$$\theta_i = \frac{\partial Y}{\partial x_i} \quad \text{(C4)}$$

where θ_i is the sensitivity coefficient.

The variance, then, may be expressed as:

$$\omega_Y^2 = (\theta_1\omega_1)^2 + (\theta_2\omega_2)^2 + \ldots + (\theta_n\omega_n)^2 \quad \text{(C5)}$$

The contribution from each uncertainty component to the overall uncertainty of the result is important when trying to determine the primary sources of uncertainty in experimental measurement. The contribution to overall uncertainty of a given measurement is found by dividing the absolute systematic contribution of a given measurement (U_i) by the total absolute systematic uncertainty:

$$\text{\% Contribution} = \frac{U_i}{\sum_{i=1}^{n} U_i} x100\% \quad \text{(C6)}$$

The absolute systematic uncertainty contribution (U_i) of a measurement is found using equation C7:

$$U_i = \left(\frac{\omega_i}{2}\theta_i\right)^2 \quad \text{(C7)}$$

where: U_i = absolute systematic uncertainty contribution of variable i,

ω_i = the uncertainty of variable i, and

θ_i = the sensitivity coefficient for variable i.

RESULTS AND DISCUSSION

SYSTEM SETUP

The system shown in Figure D1 was used to determine the collection efficiency of 1D3D and 2D2D cyclones operating at inlet velocities from 610 to 1219 m/min (2000 to 4000 sfpm).

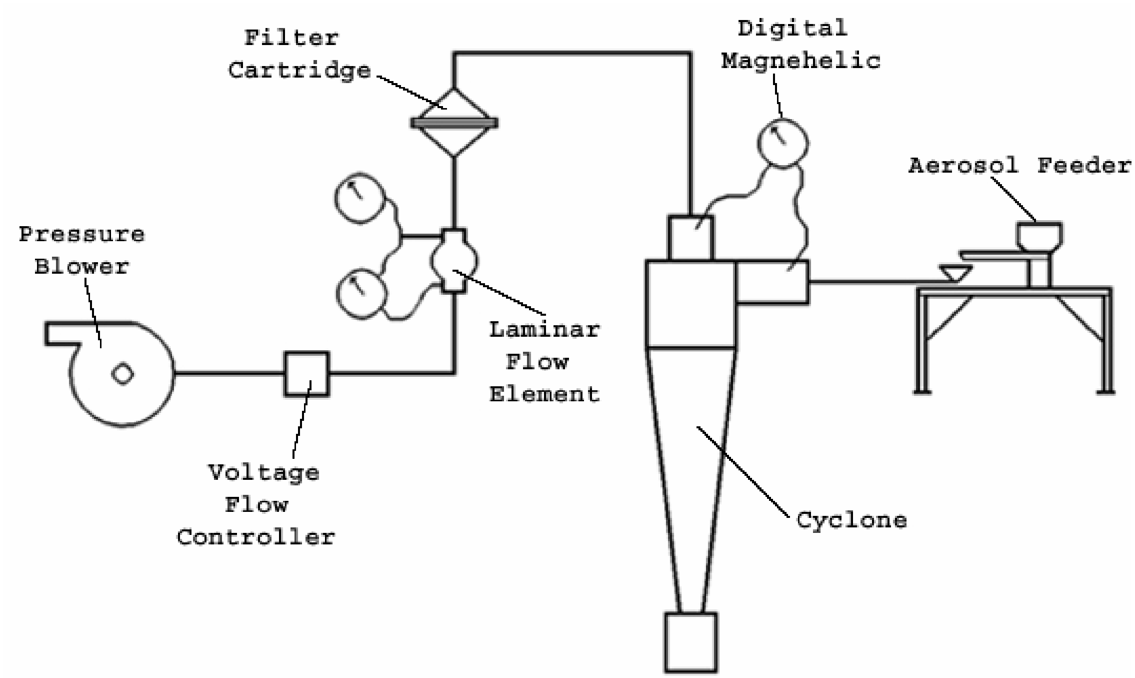

Figure C1. Cyclone testing system.

For each trial, a pre-weighed filter was placed in the filter holder and the fan was turned on. When equilibrium at the desired flow rate was reached, a measured mass of the aerosol was fed into the system using a vibratory feeder at a specified rate. The filters were then weighed again to determine the change in filter weight resulting from each trial, which corresponds to the penetration of aerosol through the cyclone.

All filters were pre-weighed and post-weighed three times using a microbalance (AG245, Mettler Toledo, Greifensee Switzerland), and the average of the filter weights were used. The mass of the aerosol entrained in the system was determined by measuring the mass of dust in a crucible using a microbalance (PB1502, Mettler Toledo, Greifensee Switzerland) and subtracting the measured mass of the crucible after the dust was placed in the aerosol feeder. The inlet velocity was determined using a laminar flow element (LFE) (Meriam Instrument Model 50MC2-2; Serial No. 773880-NI, Cleveland, Ohio), calibrated by the manufacturer to determine the flow rate of air through the system, which was subsequently divided by the inlet area of the cyclone.

PRIMARY MEASUREMENTS AND DATA REDUCTION EQUATIONS

The collection efficiency of a cyclone is measured gravimetrically according to the equation:

$$\eta = 1 - \frac{\Delta m_f}{m_{in}} \tag{C8}$$

where: η = cyclone collection efficiency (decimal),

Δm_f = change in mass of the filter (g), and

m_{in} = mass of dust entrained in the system (g).

The change in mass of the filter and the amount of dust entrained in the air stream are determined according to equations C9 and C10, respectively:

$$\Delta m_f = W_f - W_i \tag{C9}$$

where: Δm_f = change in mass of the filter (g),

W_f = mass of the filter after the test (g), and

W_i = mass of the filter before the test (g).

$$m_{in} = m_f - m_i \tag{C10}$$

where: m_{in} = mass of dust entrained in the system (g),

m_f = mass of the empty crucible (g), and

m_i = mass of the crucible and dust (g).

The collection efficiency of cyclonic separators is dependent on several factors, including the inlet velocity of air entering the cyclone at standard conditions (Wang, 2003). The standard inlet velocity of a cyclone is found using equation C11:

$$V_{std} = \frac{Q}{A}\frac{\rho_a}{\rho_{std}} \tag{C11}$$

where: V_{std} = standard inlet velocity (sfpm),

Q = actual volumetric flow rate (acfm),

A = area of the cyclone inlet (ft^2),

ρ_a = actual air density ($\#/ft^3$), and

ρ_{std} = standard air density (0.075 $\#/ft^3$).

The volumetric flow rate (Q) for these experiments was found using a calibrated laminar flow element (Meriam Instrument Model 50MC2-2; Serial No. 773880-NI, Cleveland, Ohio). The calibrated equation to determine the volumetric flow rate through the system is:

$$Q = (13.1368)(\Delta P^2) - (0.0295947)(\Delta P) \tag{C12}$$

where: Q = actual volumetric flow rate (acfm) and

ΔP = pressure drop across the laminar flow element (in. H_2O)

The area of the cyclone inlet is found by:

$$A = W * H \tag{C13}$$

where: A = inlet area (ft^2),

W = inlet width (ft), and

H = inlet height (ft).

The density of air (ρ_a) is found using equation C14:

$$\rho_a = \frac{(P_a - P_{vac}) - \phi P_{sat}}{0.37(t_{db} + 460)} + \frac{\phi P_{sat}}{0.0046(t_{db} + 460)} \tag{C14}$$

where ρ_a = density of air (#/ft^3)

P_a = atmospheric pressure (psia)

P_{vac} = negative pressure at entrance of the LFE (psia)

φ = relative humidity (decimal)

P_{sat} = saturation pressure (psia)

t_{db} = dry-bulb temperature (°F)

SENSITIVITY COEFFICIENTS

To evaluate the effect of potential errors in each primary measurement on the resulting efficiency or inlet velocity measurement, the sensitivity must be calculated with respect to each of the primary measurements. The sensitivity coefficient is calculated according to equation 4 and is based on the uncertainty of each instrument (Table C1).

Table C1. Instrument Specifications.

Parameter	Instrument	Reported Uncertainty
W_i	Metler Toledo AG Balance (AG245)	$2*10^{-4}$ g
W_f	Metler Toledo AG Balance (AG245)	$2*10^{-4}$ g
m_f	Metler Toledo Balance (PB1502)	0.02 g
m_i	Metler Toledo Balance (PB1502)	0.02 g
ΔP	Digital Manometer – Dwyer Series 475 Mark III	0.5% Full Scale
Q	LFE - Meriam Instruments Model 50MC2-2	1.064%
A	Manufacturer's Specifications	0.000625 in^2
P_a	Davis Perception II	1%
P_{vac}	Digital Manometer – Dwyer Series 475 Mark III	0.5% Full Scale
φ	Davis Perception II	5%
P_{sat}	Steam Tables	0.0001 psia
t_{db}	Davis Perception II	1°F

Using the manufacturer's reported uncertainty, the sensitivity coefficient for each variable in equations C8 – C14 were determined, using the partial differential equations described by equation C4. The partial differential equations used are contained in Appendix D.

SENSITIVITY AND UNCERTAINTY ANALYSIS

A sensitivity analysis is important when trying to determine the most influential sources of uncertainty in an experimental setup. By determining the variables with the highest sensitivity coefficient (i.e. the variables that introduce the greatest amount uncertainty into the final result), a systematic approach can be used to reduce the overall uncertainty.

The uncertainty of both the cyclone collection efficiency and standard inlet velocity were evaluated for velocity experiments with 1D3D and 2D2D cyclones using cornstarch and micro alumina. The maximum uncertainty values measured for inlet velocity (V_{in}) and collection efficiency (η) are shown in Table C2:

TableC2. Test Uncertainties.

Test	Maximum Uncertainty			
	Collection Eff. (%)	**% of η**	**V_{in} (fpm)**	**% of V_{in}**
1D3D – Cornstarch	$6.67*10^{-5}$	$6.67*10^{-5}$	79.6	5.48
1D3D - Alumina	$5.71*10^{-5}$	$5.73*10^{-5}$	79.8	4.28
2D2D – Cornstarch	$6.70*10^{-5}$	$6.70*10^{-5}$	79.4	5.34
2D2D - Alumina	$5.53*10^{-5}$	$5.55*10^{-5}$	79.2	3.83

No statistical difference in collection efficiency was detected at the 95 percent confidence level between inlet velocities of 2000 and 3100 feet per minute (fpm) for either cyclone or either aerosol. Therefore, the uncertainties associated with these results do not alter the conclusions of this research, that, when separating large aerosols from process air streams, cyclones may be operated at inlet velocities well below the Texas A&M cyclone design specifications of 3200 ± 400 fpm for 1D3D cyclones and 3000 ± 400 fpm for 2D2D cyclones without a reduction in collection efficiency.

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APPENDIX D

SENSITIVITY COEFFICIENT DETERMINATION

CYCLONE COLLECTION EFFICIENCY

EFFICIENCY

$$\eta = 1 - \frac{\Delta m_f}{m_{in}} \tag{D1}$$

where: η = efficiency (decimal),

Δm_f = change in mass of the filter (g), and

m_{in} = mass of dust entrained in the system (g).

$$\frac{\partial \eta}{\partial(\Delta m_f)} = -\frac{1}{m_{in}} \tag{D1a}$$

$$\frac{\partial \eta}{\partial(\Delta m_{in})} = \frac{\Delta m_f}{m_{in}^2} \tag{D1b}$$

MASS ACCUMULATION ON THE FILTER

$$\Delta m_f = m_f - m_i \tag{D2}$$

where: Δm_f = change in mass of the filter (g),

m_f = mass of the filter after the test (g), and

m_i = mass of the filter before the test (g).

$$\frac{\partial \Delta m_f}{\partial m_f} = 1 \tag{D2a}$$

$$\frac{\partial \Delta m_f}{\partial m_i} = -1 \tag{D2b}$$

MASS OF DUST FED INTO THE SYSTEM

$$m_{in} = m_f - m_i \tag{D3}$$

where: m_{in} = mass of dust entrained in the system (g),

m_f = mass of the empty crucible (g), and

m_i = mass of the crucible and dust (g).

$$\frac{\partial m_{in}}{\partial m_f} = 1 \tag{D3a}$$

$$\frac{\partial m_{in}}{\partial m_i} = -1 \tag{D3b}$$

STANDARD INLET VELOCITY

$$V_{std} = \frac{Q}{A}\frac{\rho_a}{\rho_{std}} \tag{D4}$$

where: V_{std} = standard inlet velocity (sfpm),

Q = actual volumetric flow rate (acfm),

A = area of the cyclone inlet (ft^2),

ρ_a = actual air density ($\#/ft^3$), and

ρ_{std} = standard air density ($0.075\ \#/ft^3$).

$$\frac{\partial V}{\partial Q} = \frac{1}{\rho_{std}}\frac{\rho_a}{A} \tag{D4a}$$

$$\frac{\partial V}{\partial \rho_a} = \frac{1}{\rho_{std}}\frac{Q}{A} \tag{D4b}$$

$$\frac{\partial V}{\partial A} = \frac{1}{\rho_{std}}\left(-\frac{Q\rho_a}{A^2}\right) \tag{D4c}$$

AIR FLOW RATE

$$Q = (13.1368)(\Delta P^2) - (0.0295947)(\Delta P) \quad \text{(D5)}$$

where: Q = actual volumetric flow rate (acfm) and

ΔP = pressure drop across the laminar flow element (in. H_2O).

$$\frac{\partial Q}{\partial Q} = 1 \quad \text{(D5a)}$$

$$\frac{\partial Q}{\partial \Delta P} = 26.2736\Delta P \quad \text{(D5b)}$$

CYCLONE INLET AREA

$$A = W * H \quad \text{(D6)}$$

where: A = inlet area (ft^2),

W = inlet width (ft), and

H = inlet height (ft).

$$\frac{\partial A}{\partial W} = H \quad \text{(D6a)}$$

$$\frac{\partial A}{\partial H} = W \quad \text{(D6b)}$$

DENSITY OF AIR

$$\rho_a = \frac{(P_a - P_{vac}) - \phi P_{sat}}{0.37(t_{db} + 460)} + \frac{\phi P_{sat}}{0.596(t_{db} + 460)} \quad \text{(D7)}$$

where: ρ_a = density of air ($\#/ft^3$),

P_a = atmospheric pressure (psia),

P_{vac} = negative pressure at entrance of the LFE (psia),

φ = relative humidity (decimal),

P_{sat} = saturation pressure (psia), and

t_{db} = dry-bulb temperature (°F).

$$\frac{\partial \rho_a}{\partial P_a} = \frac{1}{0.37(t_{db} + 460)} \tag{D7a}$$

$$\frac{\partial \rho_a}{\partial P_{vac}} = -\frac{1}{0.37(t_{db} + 460)} \tag{D7b}$$

$$\frac{\partial \rho_a}{\partial \phi} = \frac{P_{sat}}{t_{db} + 460}\left[\frac{1}{0.596} - \frac{1}{0.37}\right] \tag{D7c}$$

$$\frac{\partial \rho_a}{\partial P_{sat}} = \frac{\phi}{t_{db} + 460}\left[\frac{1}{0.596} - \frac{1}{0.37}\right] \tag{D7d}$$

$$\frac{\partial \rho_a}{\partial t_{db}} = \frac{1}{(t + 460)^2}\left[\frac{\varphi P_{sat} - P_a}{0.37} - \frac{\phi P_{sat}}{0.596}\right] \tag{D7e}$$

APPENDIX E

CALIBRATION OF THE DUST FEEDING SYSTEM FOR SIMILITUDE TESTS

A VibraScrew AccuFeeder (VibraScrew Inc.; Totowa, New Jersey) equipped with a variable speed motor was used as the dust feeding/metering mechanism for the cyclone scalability tests. The feed rate of dust was adjusted by changing the speed of the motor. Prior to conducting the cyclone scaling experiments, the feed rate of the AccuFeeder was calibrated to motor speed using No. 5 microalumina from KC Abrasives, and interactions between relative humidity, depth of dust in the feeding bin, and test number were analyzed. Test number was analyzed in order to determine if feed rate was affected by the length of time the motor had been running.

Randomized tests blocked by replication were conducted to determine the relationship between motor speed and feed rate. Motor speed was adjusted from zero to 100 percent in ten percent increments. Three replications were conducted in the morning when the relative humidity was between 60 and 65 percent, and three more replications were conducted in the afternoon, when the relative humidity was 25 percent. The feeder was run for 30 seconds at a given feed rate before sample collection started. Samples collection lasted for 60 seconds. The feeder continued to run for several seconds after sample collection ended. The mass of dust collected during the 60 second period was determined using an A&D scale, model HP-20K, with a 0.1 g resolution. The depth of dust in the feeder bin was recorded at the beginning of each test.

A linear regression was conducted to determine the relationship between dust feed rate and motor speed at each relative humidity. Both regressions resulted in R-square values above 0.997, and no statistical difference was found ($\alpha < 0.05$) between the two data sets. Therefore, the data sets were combined, and a regression analysis was conducted on the combined data set (Figure D1). The combined data set demonstrated an R-square value of 0.996.

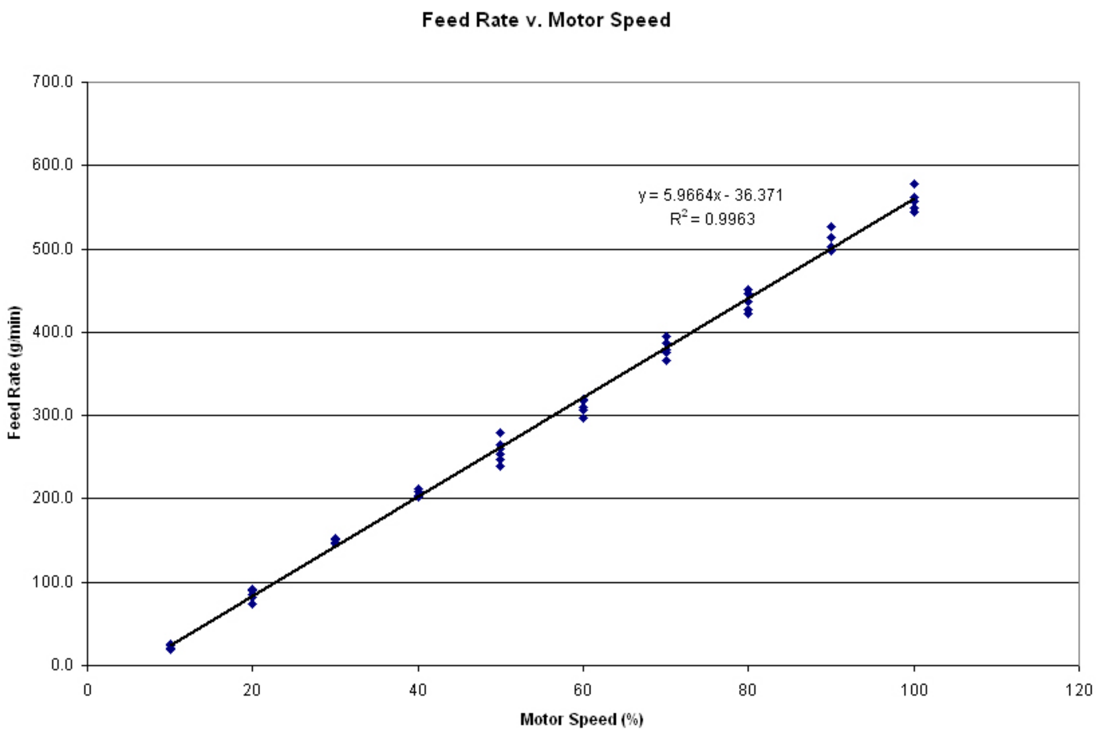

Figure D1. Feed rate of No. 5 micro alumina versus motor speed.

After determining the relationship between motor speed and feed rate, interactions between depth of dust in the feeder bin and test number were investigated. Independent regression analyses were conducted between the normalized feed rate and both of these variables. No relationship was found between the normalized feed rate and either of these variables ($R^2 < 0.01$ for both regressions). Therefore, it was determined that motor speed is the only variable significantly related to the feed rate of No. 5 microalumina using a VibraScrew AccuFeeder.

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